Transactions of the Royal Society of S. Aust. (1996), 120(1), 7-12.

THERMOLUMINESCENCE DATING OF VOLCANIC ACTIVITY AT MOUNT GAMBIER, SOUTH AUSTRALIA

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Summary

ROBERTSON, G. B., PRESCOTT, J. R. & HUTTON, J. T. (1996) Thermoluminescence dating of volcanic activity at Mount Gambier, South Australia. *Trans. R. Soc. S. Aust.* **120**(1), 7-12, 31 May, 1996.

There are several products of volcanic activity which have the potential to be dated by thermoluminescence (TL) such as lava, volcanic ash and glass, and layers of tuff and sand lying beneath a lava flow. One of the most important factors in obtaining a reliable date is the search for materials which have been sufficiently heated or bleached by sunlight to reset the TL clock at the time of the eruption. We report the investigation of a number of such materials from the Mount Gambier volcanic complex. A date of 4.2 ± 0.5 ka was obtained for the baked tuff underlying the lava flow at Valley Lake. Other results suggest that an additional event may have occurred about 7 ka ago (i.e. during the Holocene). Lava and glass samples from nearby sites had insufficient amounts of datable quartz and other samples had not been sufficiently heated but the investigation has been valuable in providing evidence of the extent to which TL dating can be applied to a context like the one at Mount Gambier.

KEY WORDS: Thermoluminescence dating, volcanism, Holocene, Mount Gambier.

Introduction

There has been a number of attempts at determining the sequence of events and the time scale involved in the formation of the volcanic complex at Mount Gambier in South Australia's South-east. The findings indicate that the volcano as we see it today is the result of a very complicated series of events, possibly spread over several thousand years. The earliest radiocarbon dates obtained by Fergusson and Rafter (1957) indicated two main periods of eruption, one at 4700 ± 70 years B.P., the other at 1410 ± 90 years B.P. These dates were incorporated into a geological history of the eruptions by Sheard (1978). Subsequently Blackburn *et al.* (1982) concluded that the most likely C-14 age was about 4 thousand years (ka) although charcoal samples were found covering the range 3.5 to 8 ka. Barton and McElhinney (1980) suggested that Mount Gambier must pre-date 5-6 ka B.P. Recently published work by Leaney *et al.* (1995) on C-14 in the inorganic and organic carbon fractions of Blue Lake sediment cores point to volcanic activity at about 7 ka. On the other hand Sheard (1995) now interprets the various C-14 ages as indicating a period of activity commencing 5-4.3 ka B.P. and extending over perhaps 300 years. Nearby Mount Schank has been dated by thermoluminescence at 4.9 ± 0.5 ka (Smith & Prescott 1987) in agreement with a palaeomagnetic measurement of Barbetti and Sheard (1981) who placed the eruptions of Mount Schank and Mount Gambier either between 1 and 5 ka or older than 7 ka.

In 1987, in collaboration with CSIRO, we embarked on a programme to date the eruptions at Mount Gambier using thermoluminescence. This technique depends on the measurement of the energy imparted to a mineral crystal over time by the ionizing radiation generated by radioactive elements in the environment and by cosmic rays; this energy is released as light when the mineral is heated in the laboratory. Its success as a dating method depends on the fact that the TL was set to zero by the event being dated, in this case either by the heat generated by the volcanic eruption or by the bleaching by sunlight of ejected material.

In the first instance samples were obtained from sites where it was considered likely that sufficient heating had taken place to reset the TL clock, and where there were likely to be sufficient quantities of quartz for an analysis. The quartz is derived from country rock sediments through which the volcanic conduit passed. The sites chosen were at Valley Lake, at Brownes Lake and at the Blue Lake crater, where there were layers of heated material underlying the lava flow. Later the scope was extended to include material which may have been blown into the air during the event, heated and/or bleached during transport and deposited in positions more or less remote from the central crater. Tuff samples were collected from several sites in the Mount Gambier and Mount Schank areas where it was thought that they might have been associated with the formation of either of the volcanoes.

Details of Samples

Details of the samples collected from the Mount Gambier complex are given in Table 1. The mineral quoted refers to the material that was extracted for the TL measurements. The quartz samples were collected and prepared according to standard practice (Huntley

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TABLE 1. *Details of the samples collected in the Mount Gambier area.*

Sample	Site	Lithology sampled	TL Mineral	Date Y/N
MG1b/3	Brownes Lake	Spatter lava	Quartz	N
MG2t/1	Blue Lake pump house	Heated tuff deposits	Quartz	Y
MG2S/1	Blue Lake pump house	Bridgewater Fm. sand below tuff and lava	Quartz	Y
MG2b/10	Blue Lake pump house	Hard tuff 10 cm below lava	Quartz	Y
			Fine grains	N
MG2c/12	Blue Lake cliff behind pump house	Upper tuff (c. 20 m above level of MG2S/1)	Quartz	Y
			Fine grains	N
MG2d/12	Blue Lake carpark	Banded upper tuff (same level as MG2c/12)	Quartz	Y
			Fine grains	N
MG4	Devil's Punchbowl	Sediment/tuff	Quartz	N
MG5S/0.1	Valley Lake, Nurses Landing	Baked tuff below basalt (0.1 m)	Quartz	Y
MG5S/0.3	Valley Lake, Nurses Landing	Baked tuff below basalt (0.3 m)	Quartz	Y
			Glass	N
MG5S/1.5	Valley Lake, Nurses Landing	Baked tuff below basalt (1.5 m)	Quartz	Y
MG5 lava	Valley Lake, Nurses Landing	Basalt	Quartz	N
MG6S/60	2 km south of Mount Gambier	Tuff, sunlight bleached	Quartz	Y
MG7	Potters Point Lookout	Ropey lava from path below tank	Quartz	N
SC10S/0.6	Mount Schank	Hard tuff layer	Quartz	Y
SC12S/a	Mount Schank	Hard layer of bedded tuff	Quartz	Y

et al. 1993), leading to extraction of 90-125 μm quartz grains, the yield amounting to 1 to 2% of the bulk dry weight. Fine grains containing a mixture of minerals were extracted from the 4-11 μm fraction.

The location of the sites is shown in Fig. 1.

The spatter lava at MG1b/3 is described by Sheard (1978) as representing the last evidence of volcanic activity. Unfortunately no material suitable for TL dating was extracted from it. The same outcome resulted from attempts to extract quartz from the ropey lava at MG7.

The MG2 site at the Blue Lake was extensively sampled from the sides of the crater just below the pump house where there are heated tuff layers covering sands of the Bridgewater Formation and from the cliff face above and behind the pump house where the tuff layers were deposited as a result of fall out from the eruptions.

The group of samples (MG4) collected near the Devil's Punchbowl contained terrestrial sediments of the Wangerrip Group from below the Gambier Limestone, dispersed in the volcanic tuff where it had been carried by the eruption. They were found not to have been sufficiently heated to make TL measurements.

The MG5S samples from Valley Lake were collected from the baked tuff at 0.1, 0.3 and 1.5 m below the base of the lava flow. It was not expected that the lowest level would have been sufficiently heated but it was included to check this point. A small quantity of volcanic glass was extracted from the MG5S/0.3 sample but this was highly magnetic and produced an insignificant TL signal. Basalt was also collected from this site. It contained very small quantities of extracted

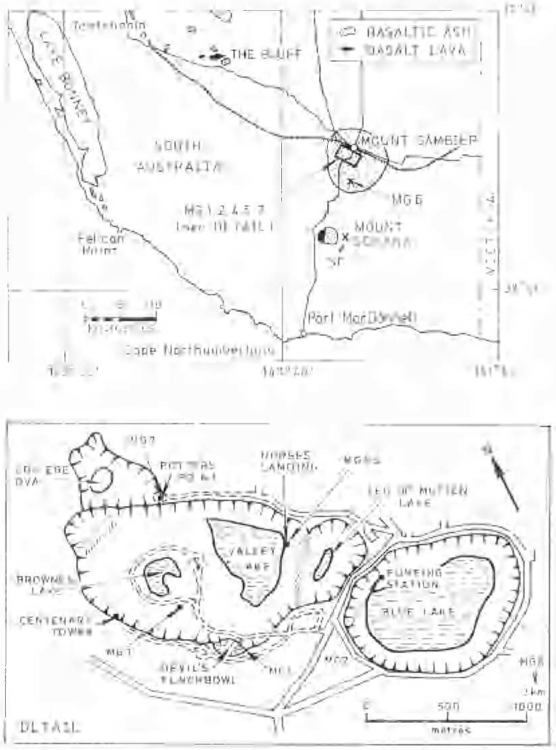

Fig. 1. Lower South-east of South Australia showing the locations of the volcanic deposits and details of the sampling sites. Adapted from Sheard (1978, 1983).

quartz, and 300 μm sections cut from the bulk sample, which might contain other minerals, yielded only low levels of TL.

Other samples of tuff and sand were collected from a site some distance to the south of the lake (MG6S/60) and from sites in the Mount Schank area (SC series), 1 km east of Mount Schank.

TL Analysis

The measurements required in order to calculate an age are the intensity of the TL in the natural sample and the TL sensitivity, as shown by the TL generated by a known amount of radiation. These two values are combined to determine the amount of radiation dose received by the natural sample, the equivalent dose. It is also necessary to measure the environmental dose rate received by the sample in the local environment. The age is then given by

$$\text{Age (ka)} = \frac{\text{Equivalent dose (Gy)}}{\text{Dose rate (Gy ka}^{-1})}$$

where the unit of radiation dose is the gray (Gy).

The TL analysis protocol was selected according to whether the samples were thought to have been zeroed by heat (samples in the MG2 and MG5 series) or by sunlight (samples from MG6 and the SC series). In the case of the heated samples the usual procedure for pottery dating was followed (Aitken 1985). In the case of the sunlight bleached samples the selective bleach method was used (Prescott & Mojarrabi 1993); the analysis to give the equivalent dose followed the "Australian slide" method (Prescott *et al.* 1993).

Dose Rate

The sample dose rates were determined by thick source alpha counting (TSAC), by neutron activation analysis (NAA), by X-ray fluorescence spectrometry (XRS) and/or by gamma-ray scintillometry (scint), as appropriate for the estimation of the elements uranium, thorium and potassium (Prescott & Hutton 1995). The concentrations of these elements are given in Table 2 together with the calculated dose rates. The samples are grouped according to type and location and it is noticeable that the baked tuff below the layer of lava has higher concentrations of all the elements than the tuff found in other locations and also the sand from the Bridgewater Formation. Consequently the dose rates in the baked tuff are about twice those in other tuff samples and higher levels of TL might be expected in these.

For each sample the quoted concentrations of U and Th agree reasonably well (within 2 sigma limits for most of the samples) among the various methods of analysis used, implying that the members of the U and Th decay chains are in equilibrium in these samples. The worst case is MG2S/1 which shows evidence of higher values for ^{238}U obtained by TSAC and scintillometry compared with the values obtained by DNA and by XRS. This situation has been shown to arise in cases of disequilibrium between the parent ^{238}U and its immediate decay products down to ^{234}U and the remainder of the decay chain from ^{230}Th to ^{210}Po occurring in samples collected in a similar environment at Mount Schank (Smith & Prescott 1987). The dose rates have been calculated to allow for the deficit in the early part of the chain, taking the extreme possibility of a value of 0.80 μg g^{-1} for ^{238}U-^{234}U and 1.49 μg g^{-1} for ^{230}Th onwards.

The dose rates were derived from the element concentrations using the conversion factors of Nambi and Aitken (1986). The values quoted in Table 2 include a cosmic ray contribution of 0.10 to 0.12 Gy ka^{-1} depending on the site (Prescott & Hutton 1994). The weighted means of the various estimates of dose rate were used in the calculation of the ages of the samples.

Age Determinations

As is usual for heat-zeroed samples, first- and second-glow growth curves were obtained and the two intercepts on the dose axis combined to obtain the equivalent dose (Aitken 1985). The growth curves were fitted to a linear relationship and used to generate the equivalent dose plateau which is shown superimposed on the natural glow curve of MG2S/1 in Fig. 2. Valid

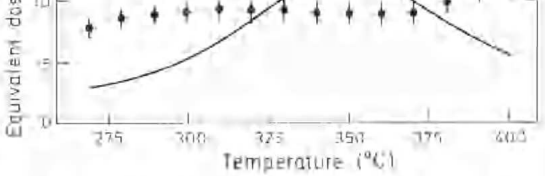

Fig. 2. Equivalent dose plateau for the MG2S/1 sample with its TL glow curve superimposed.

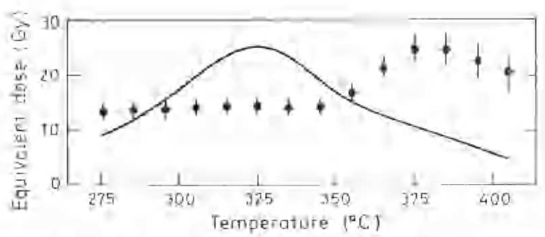

Fig. 3. Equivalent dose plateau for the MG5S/0.3 sample with its TL glow curve superimposed. The double plateau indicates two periods of heating.

TABLE 2. *Concentrations of uranium, thorium and potassium in the samples, determined by thick-source alpha counting (TSAC), X-ray fluorescence spectrometry (XRS), neutron activation analysis (NAA), delayed neutron analysis (DNA) and in situ gamma-ray scintillometry (Scint.), together with the resulting dose rates.*

Sample	Method	Uranium $\mu g\ g^{-1}$	Thorium $\mu g\ g^{-1}$	Potassium %	Dose Rate Gy ka^{-1}
Baked tuff below lava					
MG2t/1	TSAC	2.34 ± 0.48	6.43 ± 1.61		2.45 ± 0.14
	XRS	2.60 ± 0.40	8.50 ± 0.50	1.25 ± 0.01	2.67 ± 0.10
MG5S/0.1	TSAC	2.71 ± 0.27	8.04 ± 0.92		3.08 ± 0.1
	XRS	3.00 ± 0.40	10.20 ± 0.50	1.82 ± 0.01	3.32 ± 0.1
MG5S/0.3	TSAC	2.46 ± 0.41	10.79 ± 1.38		3.52 ± 0.12
	DNA, NAA	2.20 ± 0.11	9.00 ± 0.45		3.38 ± 0.06
	XRS	2.30 ± 0.40	10.40 ± 0.50	2.19 ± 0.01	3.51 ± 0.08
	Scint.	2.62 ± 0.35	8.52 ± 0.05	2.03 ± 0.05	3.47 ± 0.09
MG5S/1.5	TSAC	2.0 ± 0.3	6.9 ± 1.4		2.61 ± 0.1
	DNA	1.87 ± 0.08			
	XRS			1.59 ± 0.01	
MG5/Lava	TSAC	1.93 ± 0.35	4.59 ± 1.15		2.52 ± 0.08
	DNA, NAA	1.10 ± 0.40	5.70 ± 0.50		2.40 ± 0.08
	XRS			1.50 ± 0.01	
MG2b/10	TSAC	2.58 ± 0.38	8.49 ± 1.05		
	DNA	2.43 ± 0.09			
	XRS			2.09 ± 0.02	3.26 ± 0.22
Bridgewater Formation sand					
MG2S/1	TSAC (a)	1.44 ± 0.21	4.59 ± 0.69		1.58 ± 0.07
	(b)	1.07 ± 0.20	6.66 ± 0.65		1.64 ± 0.07
	DNA, NAA	0.80 ± 0.10	5.50 ± 0.40		1.56 ± 0.05
	XRS	0.90 ± 0.40	7.40 ± 0.50	0.60 ± 0.01	1.48 ± 0.08
	Scint.	1.49 ± 0.18	5.77 ± 0.24	0.78 ± 0.02	1.73 ± 0.05
Tuff various locations					
MG2c/12	TSAC	1.41 ± 0.26	3.03 ± 0.68		
	XRS			0.66 ± 0.01	1.27 ± 0.08
	Scint.	1.50 ± 0.12	4.32 ± 0.20	0.71 ± 0.02	1.51 ± 0.05
MG2d/12	TSAC	1.05 ± 0.40	6.32 ± 1.36		
	XRS			0.74 ± 0.02	1.50 ± 0.14
MG6S/60	TSAC	1.90 ± 0.46	4.70 ± 1.70		1.66 ± 0.13
	DNA, NAA	1.84 ± 0.19	6.24 ± 0.19		1.76 ± 0.07
	XRS			0.74 ± 0.05	
SC10S/0.6	TSAC	2.04 ± 0.33	5.11 ± 1.15		1.93 ± 0.14
	DNA, NAA	2.32 ± 0.60	7.33 ± 0.17		2.15 ± 0.15
	XRS	1.70 ± 0.17	7.70 ± 0.77	0.94 ± 0.10	2.03 ± 0.12
SC12S/a	TSAC	1.80 ± 0.39	4.06 ± 1.33		1.71 ± 0.12
	DNA, NAA	0.89 ± 0.42	5.26 ± 0.15		1.58 ± 0.10
	XRS	1.60 ± 0.16	6.70 ± 0.67	0.87 ± 0.10	1.86 ± 0.09

dating requires that there should be a distinct plateau over a range of temperature from about 300°C to 400°C (Wintle & Huntley 1982). This condition is well met in the case of sample MG2S/1. Sample MG5S/0.3 on the other hand, has two plateaux (Fig. 3). The double plateau suggests that this sample experienced two heating events, the second one of which did not reach a sufficiently high temperature to zero the TL above 350°C. It therefore yields two ages, for differing events. Analysis of the phenomenon of the double plateau is given in more detail in Robertson *et al.* (1996). The calculated ages are given in Table 3 together with the equivalent doses and the dose rates. The analysis of MG2b/10 was not completed because there was not enough pure coarse-grained quartz.

Discussion

The ages obtained show a spread of values which are not easy to interpret but it is interesting to note that in the MG samples there is evidence of events having occurred at about 4 ka and at about 7-8 ka, coincident with other methods of dating. The figures for MG5S show the single age for the 0.1 m sample and the two ages resulting from the double plateau for the 0.3 m sample. It was expected that, as the last heating raised the temperature of the 0.3 m level to no more than 350°C, the age of the 1.5 m level would be at least 7 ka, but the very much older age (98 ± 15 ka) does not fit in with the observations and the geological interpretations (Sheard 1978, 1995). It suggests that at least

TABLE 3. *Age estimates of the samples obtained from the equivalent doses and dose rates shown.*

Sample	AdTL Code	Analysis	Equivalent Dose (Gy)	Dose Rate (Gy ka^{-1})	Age (ka)
MG2t/1	95042	Heated	9.46 ± 0.47	2.60 ± 0.03	3.64 ± 0.25
MG2S/1	95043	Heated	9.13 ± 0.32	1.45 ± 0.03	6.29 ± 0.25
MG2c/12	95044	Heated	345 ± 35	1.39 ± 0.04	250 ± 30
MG2d/12	95045	Heated	82 ± 10	1.50 ± 0.14	55 ± 12
MG5S/0.1	95039	Heated	15.7 ± 1.3	3.20 ± 0.17	4.91 ± 0.48
MG5S/0.3	95040a	Heated	14.1 ± 1.3	3.46 ± 0.05	4.08 ± 0.38
	95040b	Heated	23.9 ± 2.5	3.46 ± 0.05	7.18 ± 0.75
MG5S/1.5	95041	Heated	240 ± 40	2.46 ± 0.06	98 ± 15
MG6S/60	95046	Selective bleach	14.16 ± 0.60	1.74 ± 0.06	8.14 ± 0.44
SC10S/0.6	95047	Selective bleach	3.21 ± 0.20	2.03 ± 0.08	1.58 ± 0.12
SC12S/a	95048	Selective bleach	2.23 ± 0.84	1.76 ± 0.06	1.27 ± 0.48

the quartz present in this sample was actually in place well before the eruptions occurred.

The 7 ka age found here is to be compared with that reported by Leaney *et al.* (1995) for a major change in the sedimentology of the floor of the Blue Lake. However it is difficult to reconcile the time scale of the history of the Blue Lake as set by Leaney *et al.* with the violent eruptive events traced by Sheard (1978, 1990). One possibility is that Leaney *et al.* have not sufficiently allowed for the incorporation of old carbon into their inorganic samples.

The very large ages for the tuff MG2c/12 and MG2d/12, collected from the cliff face at the Blue Lake pump house suggest that this material did not in fact become sufficiently heated during the eruptions. The very recent ages for the Mount Schank samples suggest that there was some bleaching mechanism occurring 1-2 ka ago, another date which has previously been associated with events at Mount Gambier, although it is now thought that the C-14 date on which this is based may be due to intrusive tree root charcoal (pers. comm. Blackburn to Sheard 1995).

Because of the problem in TL dating of determining whether the event that is being dated removed all the existing stored energy, all the dates should be carefully considered with regard to other evidence. For example, do the two apparent groups of ages obtained, i.e. c.4 ka and c.7 ka really indicate two eruptions separated by 3 ka? During this time interval there should have been considerable weathering of any tuff ejected. However, the chemistry of the tuff samples MG5S/0.1, MG5S/0.3 and MG2S/1 tuff (grouped together in Table 2) shows that the ratio of the more soluble and mobile elements, sodium, magnesium and phosphorus to the insoluble element, titanium, is the same as that found for the solid lava. Thus the lava must have protected the tuff very soon after it was deposited. There are also no known palaeosols developed within this tuff or on top of the lava (Sheard 1990). The exposed tuff MG6S/60 does show considerable weathering with the loss of about 50% of the soluble elements in relation to titanium. Incidently the loss of elements from MG6S/60 is about the same as the loss of the same elements from the similar site SC10S/0.6 near Mount Schank. The age of the Mount Schank eruption was found to be 4.9 ± 0.5 ka by Smith and Prescott (1987) using well baked tuff/sand under the lava flow and the age of MG6S/60 should be similar. These chemical considerations support the suggestion that neither heating nor exposure to sunlight has been sufficient in some of the samples to remove all of the pre-existing TL.

M. J. Sheard (pers. comm.) states, "The phreatic style of eruption so evident at Mount Gambier (i.e. associated with copious H_2O) means that many eruptive products incorporating exotic quartz may not have been raised much above 100°C. . . . In addition, under high volume tephra explosions some or most of the exotic quartz could escape light bleaching (i.e. re-setting) due to ash cloud or surge cloud density and subsequent rapid fallout and burial. Thus, it is possible to have exotic quartz grains, only partially reset or left with their "older" TL signature, incorporated into much younger tephra." Sheard's remarks seem to indicate the possibility of finding samples containing partially heated quartz grains mixed with thoroughly bleached tephra, and so possibly being able to detect different dates for different sized grain fractions. With this end in view, an attempt was made to date the fine grain fraction of the samples from which quartz grains had been extracted, but it was found in the three samples tested (MG2b/10, MG2c/12 and MG2d/12) that either there were insufficient fine grains or that the fine grains showed no TL and no sensitivity to radiation.

The TL dates in conjunction with other geochronological evidence have reinforced the belief that there was volcanic activity at Mount Gambier at about 4 ka ago, and that there may have been activity at 1.5 and 7 ka, but that the latter dates should be accepted with caution. The investigations have also illustrated that

it is often difficult to select appropriate samples for TL dating from a complex system like the one at Mount Gambier.

Acknowledgments

The late John Hutton was associated with all of the work described here. It is a matter of regret that he did not see the final publication. The project was begun in collaboration with CSIRO and the work was supported by CSIRO and the Research Fund of the University of Adelaide, and by AINSE. Kym Lawry, Adrian Murphy and Phillip Stamatelopoulos assisted with the work. M. Sheard and D. Leaney gave much useful advice.

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